A Two-Component Element for Modeling Strain Localization in Materials

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Many ductile materials are prone to strain localization (shear banding), particularly when they are under high-rate, dynamic loading conditions (such as impact and explosive-loading). Strain localization refers to the formation of highly localized deformation in the form of narrow planar bands of large plastic strains from an initially smooth deformation field. Although these planar bands of localized deformation are often called shear bands, the mode of deformation (i.e., the strain tensor) inside the bands can have both normal and shear components. A tensile normal strain can cause void growth and even form open cracks inside the band. The cause for strain localization is material instability, which can be caused by a variety of physical mechanisms: thermal softening, damage due to nucleation and growth of microcracks and voids, sudden strain-rate drop in the material after a shock passage, effects of texture in anisotropic materials, nonassociative flow behavior, or changes in microstructures such as phase transition due to shock loading. In a recent study of uranium alloyed with 6% niobium (U6), we have found that the alloy can become plastically unstable at modest strain levels in the post-shocked condition [1]. The post-shock condition refers to the material properties after processing by a large amplitude shock wave.

Once a localization band forms in a smooth, uniformly deforming specimen, the deformation field becomes highly nonuniform, with the materials inside the band accounting for almost all the specimen deformation while the bulk material outside the band experiences little further straining (often the outside material unloads elastically to accommodate softening inside the band). One important consequence of this highly nonuniform deformation is that the material inside the bands can have a plastic strain very close to its ductility (the value of plastic strain where failure occurs) while the overall deformation is still fairly modest. Clearly, it is important to understand and properly model shear bands in order to properly model failure of such materials.

Computational modeling of strain localization has previously used the approach of direct numerical simulation, where refined meshes are used to resolve the band features. While it is within the reach of today's computational power to conduct such direct simulations for simple, laboratory-scale structures, it is impractical for a designer to perform routine simulations with such high resolution to address the much more complex three-dimensional (3-D) weapon system. To resolve the band structure would require a mesh size less than the thickness of the bands that are initially of the order of 100s of microns. Constraint of reasonable aspect ratios of computational elements would require millions of elements for even a simple geometry. In an explicit analysis code, tiny elements also require very small time steps due to the stability requirement. The objectives of the current work are to develop a computational model to incorporate localization bands within an element, and to implement the model in a finite-element analysis (FEA) code. The main advantage will be that larger elements (orders of magnitude larger than the shear band thickness), longer time steps, and subsequently less computational time can be used to render a more accurate engineering analysis.

Figure 1 shows schematically the new element containing a thin planar band of localized deformation (shear band). The band centers at the centroid of the element and extends across the element. For an imposed strain there are two sets of strains in the element: that inside the shear band, and the "matrix" strain.

To determine these strains, three conditions are used: 1) the difference in the strain rates inside and outside satisfies the Maxwell compatibility condition, 2) the sum of deformations in the band and matrix matches with the imposed element deformation, and 3) the traction vector is continuous across the band.

The new element has been implemented into EPIC, a 3-D, explicit, FEA code for large strain, high strain rate dynamic applications. Figure 2 is a snapshot of the strain distribution in a thin U6 plate under tension. (The strain shown is the normal component along the direction of loading.) The plate is 1 inch square with a thickness of 1/12 inch and is pulled at the top and bottom edges. The material properties used in the calculation simulate U6 under post-shocked condition. Figure 2 shows that, at the background strain of about 0.25, the deformation has localized into two thin bands and one of which (starting from the lower left corner) dominates where the strain reaches 0.4. This numerical result is consistent with our earlier study of a U6 hemi loaded with explosives [1], in which we demonstrated that processing of a large-amplitude shock can have a significant effect on material instability and strain localization.

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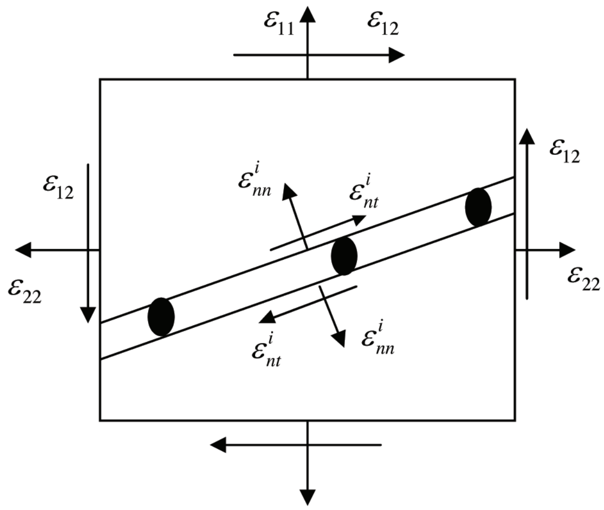
[1] G.T. Gray, et al., "Predictive Capability for Deformation and Damage in Metals: The Synergy Between Experiments and Modeling," *Los Alamos Science* **29**, 80–93 (2005); also *ASM Int. J. Failure Analysis and Prevention* **5**, 7–17.



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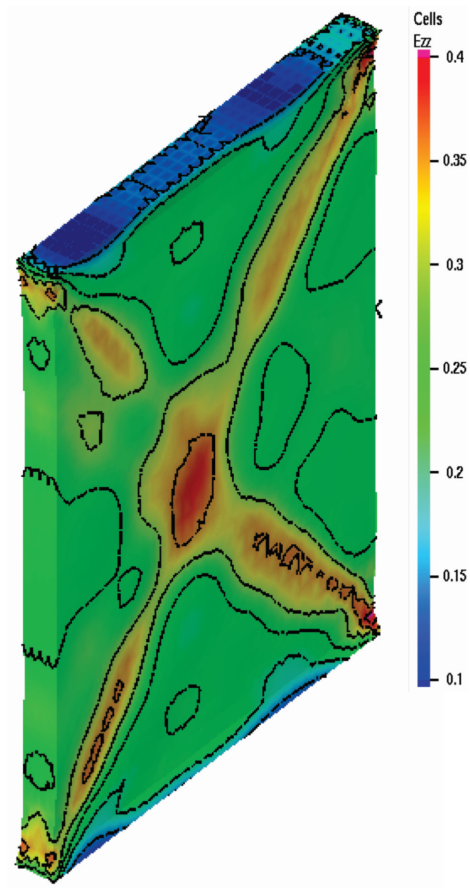

Fig. 2.
A snapshot of the strain distribution in a thin U6 plate under tension. (The strain shown is the normal component along the direction of loading.)

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